Dynamic magnetic properties of epitaxial MnAs thin films studied by spin-wave Brillouin scattering

著者	水口　将輝
journal or publication title	Journal of Applied Physics
volume	95
number	11
page range	6619-6621
year	2004
URL	http://hdl.handle.net/10097/47371

doi: 10.1063/1.1682951

JOURNAL OF APPLIED PHYSICS VOLUME 95, NUMBER 11 1 JUNE 2004

Dynamic magnetic properties of epitaxial MnAs thin films studied by spin-wave Brillouin scattering

A. Murayama,[a] K. Hyomi, M. Sakuma, and Y. Oka
Institute of Multidisciplinary Research for Advanced Materials (IMRAM), Tohoku University, 2-1-1 Katahira, Sendai 980-8577, Japan

J. Okabayashi, M. Mizuguchi, H. Kuramochi, and H. Akinaga
SYNAF, National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba Central 4, 1-1-1 Higashi, Tsukuba 305-8562, Japan

(Presented on 6 January 2004)

Dynamic magnetic properties of epitaxial MnAs thin films are studied by means of Brillouin light scattering (BLS). The sharp spectral peaks of the inelastic BLS are observed in room temperature, which are attributed to surface spin waves indicating the long-wavelength collective behavior of ferromagnetic spins. The field dependence of the surface spin-wave frequency is strongly affected by an in-plane angle between the crystal axis and the external field direction in a GaAs(100)/MnAs(-1100) film, which originates from uniaxial magnetic anisotropy parallel to the MnAs[11-20] axis and the modified g value. Significant damping of the spin-wave BLS spectrum is observed with increasing excitation laser power, possibly due to thermal effects. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1682951]

A MnAs thin film is one of the important candidates for spin-electronic materials, since the MnAs can be epitaxially grown on a GaAs surface and shows ferromagnetic properties in room temperature (RT).[1,2] The crystal structure of the MnAs on the GaAs in RT is the NiAs-type hexagonal. The ferromagnetic properties of the bulk MnAs were studied and the Curie temperature T_c was obtained as 313 K. T_c was discussed in terms of the exchange magnetostriction mechanism.[3] Recently, the detailed temperature dependencies of the magnetization and the strain have been reported in the epitaxial MnAs films.[4]

The dynamic magnetic properties of the MnAs are important and should be evaluated for the applications to ultrahigh-speed magnetic and spin-electronic devices. However, the dynamic properties of the ferromagnetic spin system in the MnAs are not well known yet. Therefore, we have studied the dynamic magnetic properties of the epitaxial MnAs thin films by means of Brillouin light scattering (BLS). The dynamics of the collective behavior of ferromagnetic spins, that is, ferromagnetic spin waves, can be studied in a gigahertz frequency region by the BLS technique.[5] The spin waves with the wavelength comparable with that of an excitation light were detected in many ferromagnetic thin films, and the high sensitivity suitable for the study of magnetic ultrathin films and nanostructures was achieved. Magnetic parameters, such as the g factor, the saturation magnetization and its direction, the magnetic anisotropies, and the magnetic effective thickness, can be determined from the field dependence of the spin-wave frequency and the angle dependence of that between the crystal axis and the external field. The g value is especially important, since the rotation of the magnetization will be affected by the g value including the damping factor in the gigahertz frequency domain.

[a]Author to whom correspondence should be addressed; present address: IMRAM, Tohoku University, 2-1-1 Katahira, Sendai 980-8577, Japan; electronic mail: murayama@tagen.tohoku.ac.jp

The single crystal MnAs films with the thickness of 50 nm were grown on GaAs(100) and (111) substrates by a conventional solid-source molecular beam epitaxy. GaAs overlayers with the thickness of 5 nm were subsequently deposited on them.

The BLS spectra were observed in RT (295 K) by using a tandem six-pass Fabry-Perot interferometer.[6] The second-harmonic light of a Nd:YAG (where YAG stands for Yttrium aluminum garnet) laser with the wavelength of 532 nm was used as an excitation source. A single longitudinal mode of the laser light with linear polarization was introduced to the sample surface with an incident angle of 45° for the film plane. A magnetic field up to 1.5 T was applied parallel to the sample surface and normal to the linear polarization of the excitation light. An inelastic scattering light was collected with a linear polarizer perpendicular to the polarization of the excitation light in a backscattering geometry, in which the inelastic scattering only due to the spin waves can be detected in this experimental geometry. A photomultiplier with the dark count of 1.2 cps was used for detecting light scattering spectra.

Sharp peaks of BLS spectra were clearly observed in RT with the laser power of 50 mW. Frequency shifts of the BLS peaks as a function of magnetic field in a GaAs(100)/MnAs (-1100) film are shown in Fig. 1. The field was applied parallel to the GaAs[110]//MnAs[11-20] (a axis) direction, which was in plane, and the polarization of the incident light was normal to it. Two spectral peaks are observed and the field dependencies of both peaks are similar. These BLS peaks originate from the ferromagnetic spin waves, since they are excited and show marked frequency shifts without an external field. In BLS, surface spin waves as well as standing spin waves with the wavelength comparable with that of the excitation light can be detected. The frequencies of the spin waves observed, here correspond to the surface spin waves, rather than the standing spin waves. Also, it is supported by the fact that the intensity of the BLS spectrum

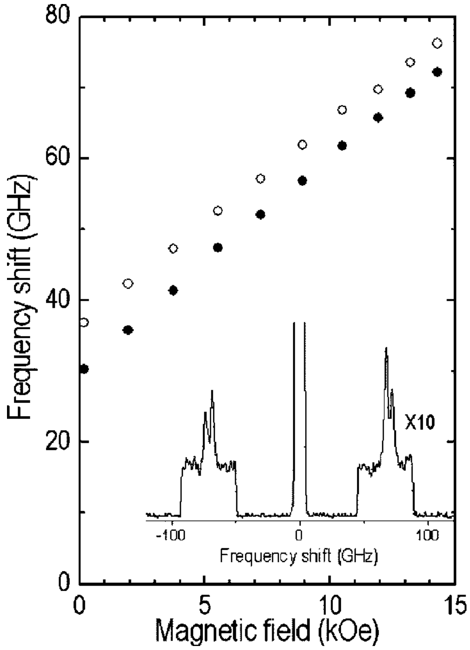

FIG. 1. Frequency shifts of the BLS peaks as a function of magnetic field in the GaAs(100)/MnAs(-1100) film. The external field was applied parallel to the crystal axis of GaAs[110]//MnAs[11-20] and the polarization of the incident light was normal to it. The inset shows a typical BLS spectrum in 13.2 kOe and the excitation laser power was 50 mW.

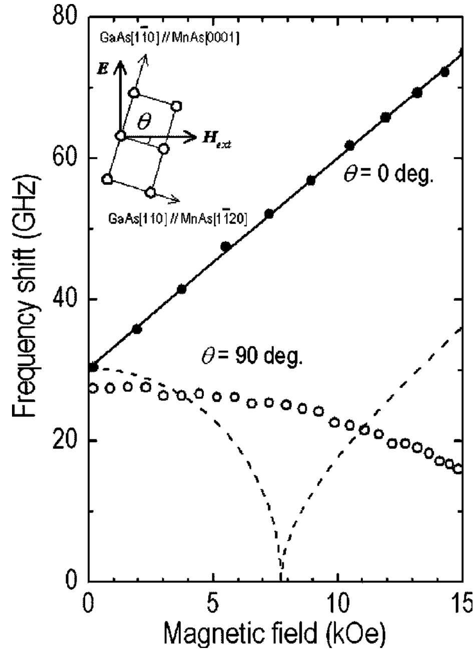

FIG. 2. Spin-wave frequency as a function of magnetic field for the in-plane angle $\theta = 0°$ (closed circle) and 90° (open circle) between the field direction and the crystal axis of GaAs[110]//MnAs[11-20]. The solid line is a calculation for the spin wave with $\theta = 0°$ and the broken line indicates that for $\theta = 90°$ taking the magnetization direction into account.

in an anti-Stokes process (positive frequency shift) is higher than that in a Stokes process, which is characteristic of the surface spin wave. The in-plane angle dependence of the frequency difference between those two spin-wave modes is similar, which shows that the two modes do not originate from changes in the anisotropy direction possibly due to different orientations of the crystal axis of grains. The saturation magnetization M_s was shown to be highly sensitive to strain for the *a* axis on the MnAs(-1100) plane.[4] Therefore, those two spin-wave modes can be attributed to different strained states in the film since the spin-wave frequency is a function of M_s, although the spatial distribution of the strain is not clear.

When an external field is applied parallel to planes of the MnAs films, the field dependence of the surface spin-wave frequency in the GaAs(100)/MnAs(-1100) film is found to be different from that in the MnAs(0001). For the MnAs(-1100) film, the field dependence of the surface spin-wave frequency is strongly affected by the angle θ between the crystal axis and the external field direction. Meanwhile, it is independent for the MnAs(0001). The spin-wave frequency is plotted as a function of magnetic field with two angles, $\theta = 0°$ and 90°, for the GaAs[110]//MnAs[11-20] axis, in Fig. 2. Here, one of the two spectral peaks with higher intensity is plotted. We compare the data with the frequency of the uniform spin-wave mode to understand the phenomenon. The lines show the spin-wave frequencies of the uniform mode calculated to fit the experimental data taking the uniaxial magnetic anisotropy and the magnetization direction into account. The uniform mode is based on the uniform precession motion of spins. The frequency of the surface mode is different from that of the uniform mode due to the thickness effect. However, such difference becomes small when the anisotropy field is high. It is evaluated as about 1 GHz at 0 kOe in this case.

The existence of in-plane uniaxial anisotropy was known from the static magnetization curves and the easy axis for the magnetization was GaAs[110]//MnAs[11-20]. From the fitted calculation for the data with $\theta = 0°$ (solid line), the *g* value of 2.2, the saturation magnetization $M_s = 500\ \mathrm{emu/cm^3}$, and the in-plane uniaxial anisotropy field $2K_u/M_s = 7.8\ \mathrm{kOe}$ are deduced, where the magnetization lies along the external field. The M_s value is obtained as $520\ \mathrm{emu/cm^3}$ in RT from the magnetization curve for the easy axis. It was difficult to determine the value of the anisotropy field from the magnetization curve for the hard axis, since the slope of the magnetization curve was not linear. On the other hand, the calculation for the hard axis (broken line) cannot reproduce the field dependence of the experimental data with $\theta = 90°$, where the magnetic parameters determined from the above field dependence with $\theta = 0°$ are used. In this calculation, the uniform rotation of the magnetization from the easy axis toward the hard axis with increasing external field is considered. At a critical field of 7.8 kOe, the spin-wave frequency becomes 0 GHz in the calculation, due to the cancellation of the effective fields acting on the magnetization, including the external field, the uniaxial anisotropy field, and the shape anisotropy field. Below this critical field, the tendency of the field dependence of the spin-wave frequency agrees with the experimental data. However, around the critical field, the steep drop in the spin-wave frequency, as expected in the calculation, was not observed. The domain formation was pointed out as a possible cause to prevent observations for such steep drop in the spin-wave frequency at the critical field.[7] Actually, in our magnetic force microscope observations, magnetic domains with the

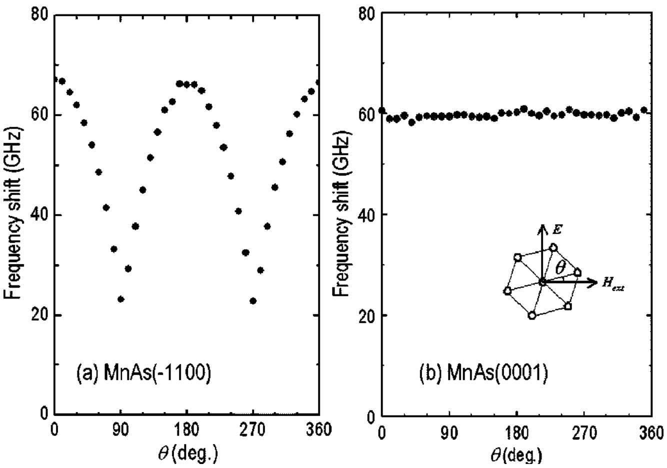

FIG. 3. The spin-wave frequency as a function of θ in the MnAs(-1100) film (a) and the MnAs(0001) film (b). The external field was 11.9 kOe.

dimensions of sub-micrometers were seen in zero external field.

Above the critical field, the sign of gradient of the field dependence is opposite between the calculation and the experimental data. It means that the sign and value of the g factor also depend on the θ, if the magnetization has completely rotated to the field direction. The spin-wave frequency as a function of θ on the MnAs(-1100) plane is shown in Fig. 3(a). In high fields, the θ dependence of the spin-wave frequency shows uniaxial behavior. It is explained mainly by the uniaxial anisotropy discussed above, which is confirmed by the field dependencies of the spin-wave frequency with various θ. Above $\theta = 60°$, the gradient of the field dependence in high fields starts to move away from the calculation based on the uniaxial anisotropy and $g = 2.2$. Such discrepancy increases systematically with increasing θ, suggesting additional changes in the g value. Nonuniform rotation of the magnetization toward the hard axis of GaAs[1-10]//MnAs[0001], possibly due to the pinning effect, also can modify the field dependence of the spin-wave frequency with large θ. However, the magnetization curve for the hard axis almost saturates around 15 kOe and thus such effect can be negligible. Without external field, the spin-wave frequency shows no significant θ dependence, since the magnetization directs to the MnAs[11-20] axis. Only the amplitude of the precession, which affects the BLS intensity, depends on the θ. In addition, the spin-wave frequency is also constant with respect to the θ rotation in the MnAs(0001) film, as shown in Fig. 3(b). Therefore, the uniaxial anisotropy observed on the MnAs(-1100) plane can be attributed to the crystal structure and the strain. In the MnAs, the distance between the Mn atoms is relatively large and the Mn atoms are isolated in part by the As atoms. Therefore, the exchange integral between Mn atoms can be modified by the slight changes in the crystal structure as well as the electron band structure. Recent theoretical work shows that the small changes in the hybridization between the d- and p-like bands can cause significant changes in the magnetization.[8] Such band-related picture including p-orbital character for the ferromagnetism suggests the strain-induced uniaxial anisotropy and the modification of g factor, rather than isotropic g factors in localized d-electron systems.

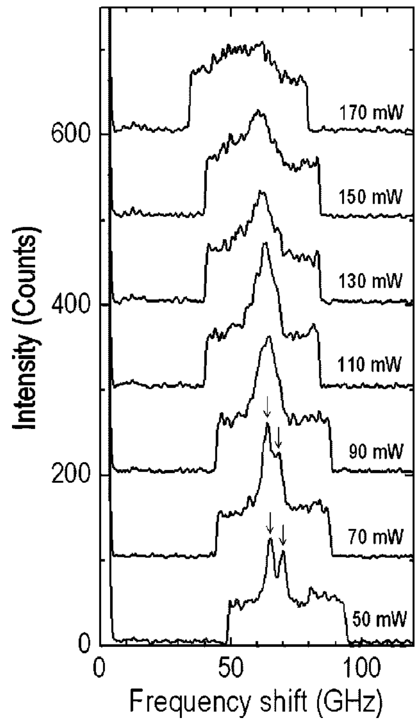

FIG. 4. The spin-wave BLS spectrum as a function of excitation laser power in the MnAs(-1100) film. The external field was 11.9 kOe and $\theta = 0°$.

Finally, we show that the BLS spectrum is significantly damped with increasing laser power. The spin-wave BLS spectrum as a function of excitation laser power in the GaAs(100)/MnAs(-1100) film is shown in Fig. 4. The spectrum width increases and the intensity decreases with increasing laser power, while the spin-wave BLS intensity is expected to increase with increasing laser power. It can be attributed to thermal effects due to the laser heating, since the T_c is 313 K and is close to RT. The spectrum splitting indicating two spin-wave modes disappears with the laser power of 90 mW. It can be understood by the fact that the strain and resultant M_s are strongly affected by the temperature. The inhomogeneous broadening due to local changes in the M_s suppresses the spectral splitting. However, the averaged M_s value and the large in-plane anisotropy still remain under high power excitation as 110 mW in the MnAs(-1100) film, since the spin-wave frequency is significantly not decreased. The scattering intensity starts to decrease at 90 mW, as well as the spectrum broadening. Therefore, the damping of the long-wavelength surface spin waves is suggested to be highly sensitive to the temperature.

This work was supported in part by the NEDO Nanotechnology Materials Program and also the Ministry of Education, Science, and Culture, Japan. A.M. acknowledges the support of the Sumitomo Foundation.

[1] M. Tanaka *et al.*, J. Appl. Phys. **76**, 6278 (1994).
[2] M. Tanaka *et al.*, Appl. Phys. Lett. **65**, 1964 (1994).
[3] R. W. DeBlois and D. S. Rodbell, Phys. Rev. **130**, 1347 (1963).
[4] A. K. Das *et al.*, Phys. Rev. Lett. **91**, 087203 (2003).
[5] B. Hillebrands, in *Light Scattering in Solids VII*, edited by M. Cardona and G. Güntherodt (Springer, Berlin, 1999), p. 174.
[6] A. Murayama, K. Hyomi, and C. M. Falco, Phys. Rev. B **61**, 8984 (2000).
[7] A. Murayama *et al.*, J. Magn. Magn. Mater. **198–199**, 372 (1999).
[8] S. Schwieger and W. Nolting, Phys. Rev. B **64**, 144415 (2001).